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FATIGUE CRACK FORMATION ON ANNEALED AND PRESTRAINED PURE ALUMINUM

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Initial fatigue cracks on annealed and prestrained specimens of pure aluminum were observed. Intergranular cracks appeared on annealed and slightly prestrained specimens relating to specific slip bands, and decreased or disappeared on highly deformed specimens on which slip band cracks and sub-boundary cracks formed. Those cracks were discussed by relating to X-ray diffractions and hardness distributions around grain boundaries.

INTRODUCTION

Many theories and criteria on fatigue crack formations have been proposed, some of them relate to glides and/or slip bands of crystals such as intrusions and extrusions, and others to behavior of dislocations making subgrains and/or substructures. The investigations on mechanism of intergranular crack formation, however, have not been so many, because the plastic deformation at and near the grain boundaries by cyclic strainings is very complicated.

The author observed slip bands and cracks in detail by using an optical and scanning electron microscope, classified the slip bands to three types, and found out a specific relationship between the slip bands patterns and intergranular cracks on annealed specimens. On the other hand, such intergranular cracks decreased or disappeared on plastically prestrained specimens. The local plastic deformations were detected by microbeam X-ray diffractions and the hardness neighbour the grain boundaries was measured.

CRACK FORMATION

The fatigue crack formations may be classified as follows; (1) Slip band crack; (2) Sub-boundary crack; (3) Intergranular crack and (4) Tearing crack. In the case of small amplitude stress or strain, those cracks can be seen at early stage of crack propagation except (4). They, however, are not necessarily seen at the same time.

Let us review the mechanism of them as follows;

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(1) Slip band crack

The slip bands develop in fatigue process, then intrusions and extrusions also grow up. Wood et al[1] observed that the intrusions developed to become or produce cracks.

(2) Sub-boundary crack

Dislocations increase, re-arrenge and/or tangle in fatigue process. Then substructures or subgrains, about 2 μm in size, develop and dislocation dencity becomes so high at the sub-boundary that microcracks occure there. Grosscreutz et al[2], Wood et al[1] and many other researchers shew those phenomena in highly deformed regions such as tip of propagating crack on transmission electron micrographs. The development of substructures could also be detected by microbeam X-ray diffractions.

(3) Intergranular crack

When plastic glides in grains are restricted at incrusions or grain boundaries, many dislocations pile up there and induce high stress concentrations near the slip ends. Such high stress may produce a crack. Zener[3] initially proposed that model, Mott[4] confirmed the existence of such cracks and Stroh[5] developed that theory.

The author[6] proposed the mechanism of intergranular cracks on annealed specimens of pure aluminum as follows; A crystal orients in an easy glide direction and neighbours in different directions, then former glide to a grain boundary and the slips are restricted there as shown in Fig. 1. Dislocations should pile up and microcracks also occure on the intergranular. This mechanism of crack formation is same one as proposed by Zener, but different at the viewpoint of stress concentration. This model does not need the high stress concentration because of following mechanism; when many micocracks array on the intergranular and the cohesion of the grain boundary greatly decreases, then the cracks connect with each other.

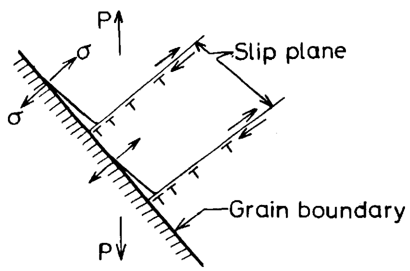


Fig. 1 Mechanism of intergranular crack formation proposed by the author.

EXPERIMENTAL PROCEDURES

(1) Specimens

The specimens used were pure aluminum, 99.99 %, and were of the shape as shown in Fig. 2. They were completely annealed and electro-polished. The grain sizes of them

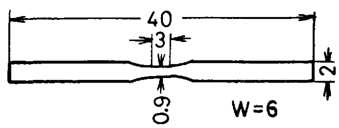


Fig. 2 Specimen.

were from 0.3 to 2 mm in diameter. Those specimes were cyclically strained in tension and compression with constant stress amplitude, and the frequency was 900 cpm.

(2) Observations on slip bands and cracks

The slip bands were often observed in the fatigue processes with an optical microscope mounted on the fatigue test machine. The observation of cracks was difficult by using it, but easy by the scanning electron microscope (SEM). Most of the microcracks were found out by SEM, The slip band cracks, however, could hardly be distinguished from the slip bands.

(3) Microbeam X-ray diffraction

Microbeam X-ray, 0.15 mm in diameter, was used to detect the crystalographic orientations of grains and local plastic deformations. The diffraction patterns were Laue spots because the grains were bigger than the diameter of X-ray. The spots on transmission Laue diffractgraphs elongated in radial, and on back refrection broadened. Occasionally, Debye patterns by Co K_α X-ray appeared when the substructures of grains sufficiently developed as to be poly-crystals.

RESULTS

(1) Slip band patterns

The slip bands produced by cyclic strains on pure aluminum can be classified as follows; Pattern I; Slip bands are straight and long in direction of about 45 degrees to the loadings. Pattern II; The slip bands are wavy in the direction from 60 to 80 degrees. Pattern III; The slip bands are meshlike in the direction of 45 degrees. The examples of these patterns on a specimen loaded about 10^6 times with strain amplitude of 0.05% are shown in Fig. 3. The grains E, H and K are pattern I, A,B,C and F are II, I,N and O are III. The examples of them observed with SEM are shown in Fig. 4 in which the patterns are of II and III, and the typical pattern I is in Fig. 5. The pattern II seems as to be extrusions.

The crystalographic orientation of grains occured pattern I is in the direction of easy glide to the loadings, and {100} planes face on surface, that is, the slips are parallel with the surface. The slips of pattern III can be considered that the glides on different kinds of two planes, {111}, occured at the same time. The orientation of the crystal occured the slip bands of pattern III is near of that of pattern I. The orientation of crystals of rattern II is uncertain.

These patterns can be seen both on annealed and prestraind specimens. The intergranular cracks tightly relate to the slip bands of pattern I on annealed and slightly prestained specimens as following.

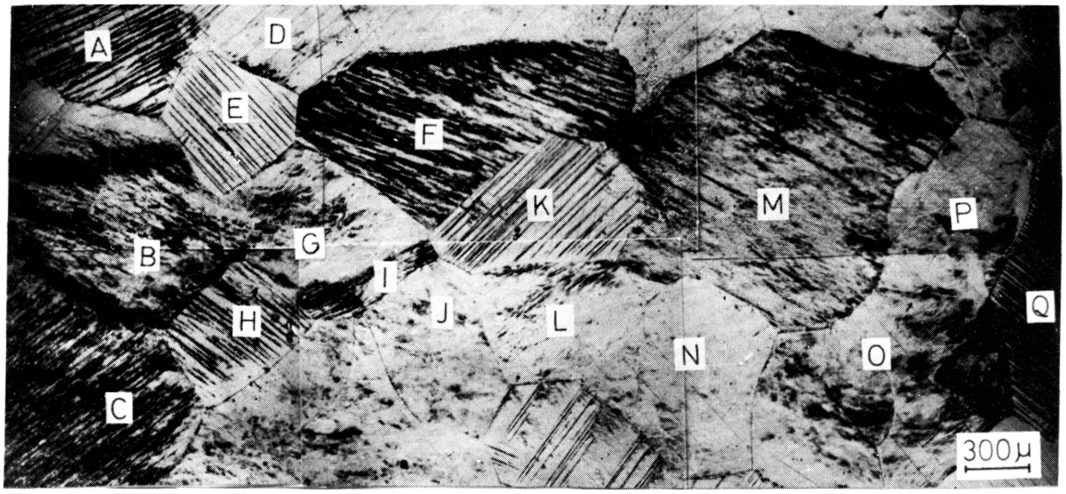


Fig. 3 Slip patterns, ε_a=0.05%, n=10^6

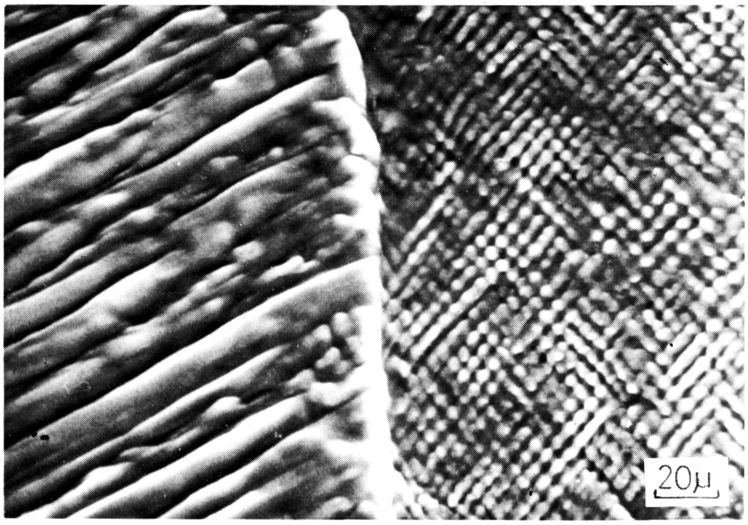


Fig. 4 Examples of slip band patterns II (left) and III (right)

(2) Crack formation on annealed specimens

Most of fatigue cracks on annealed specimens initiated on intergranulars independent of strain amplitudes and fatigue lives. A few examples of those cracks are shown in Fig. 5. All of these cracks relate to slip pattern I as following; The glides occured toward a grain boundary on which the crack was formed and did never connect with the next grain. If the glides connected to the next grain, no intergranular crack was formed. These fects are able to confirm the mechanism of the intergranular crack.

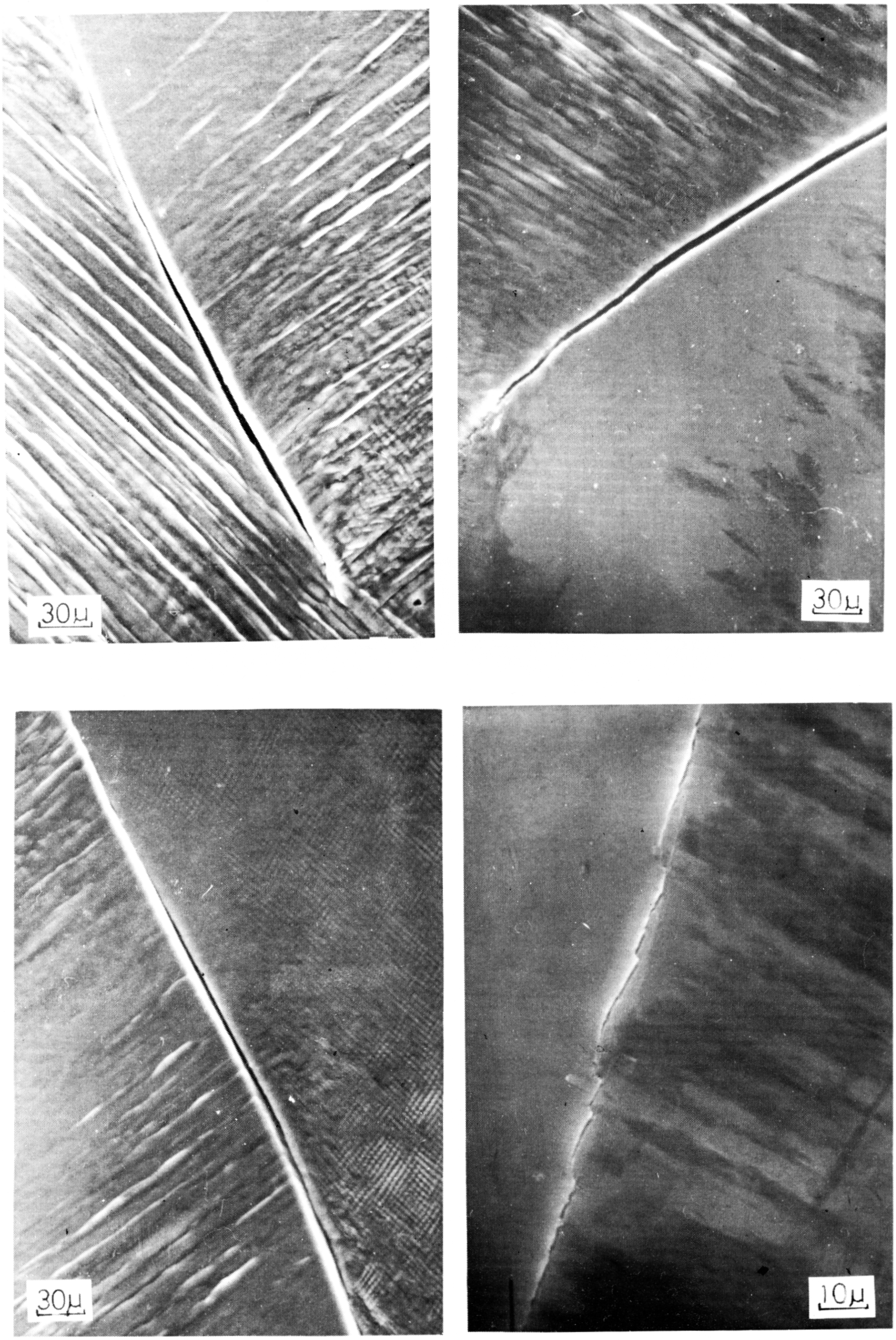


Fig. 5 Intergranular cracks on annealed specimens.

Much elastic and plastic strains were stored in close vicinity to the grain boundaries on which the cracks occured, they were detected by micro-beam X-ray diffractions as shown in Fig.6 and Table 1. Fig. 6 shows the Laue spots elongated which were obtained on and near the grain boundary. Table 1 shows the comparison of values of elongations and widths.' It can be known from them that the distortions near the grain boundary are larger than those at the mid points of grains.

A few cracks could be seen in the grains of pattern III, but no crack in the slip bands of pattern I and II on annealed specimens. It must be noted that although the slip bands of pattern II are seen like the extrusions and intrusions, the cracks have never be seen.

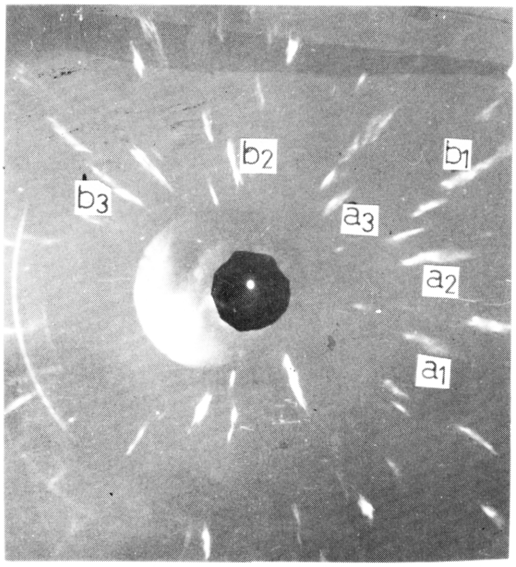


Table 1 Comparison of magnitudes of broadening of transmission Laue spots.

	Length	Width
Grain-boundary	0.14	0.024
Inside of grain	0.11	0.011

unit: radian; mean velues

Fig. 6 Transmission Laue spots elongated. Symbols a and b show the different grains.

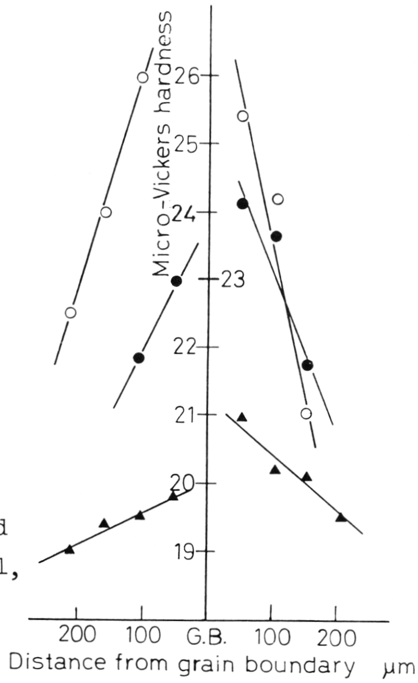


Fig. 7 Hardness distributiobs around the grain boundaries on 7% elongated specimen.

(3) Crack formation on prestrained specimens

Some specimens annealed were plastically tensioned before cyclic loadings, the static strains were from 2.5 to 7.0 %. The hardness in close vicinity to grain boundaries increased as shown in Fig. 7. If the prestrain was small, the fatigue cracks were formed both on grain boundaries and inside of grains as shown in Fig. 8. As the prestains increased, the

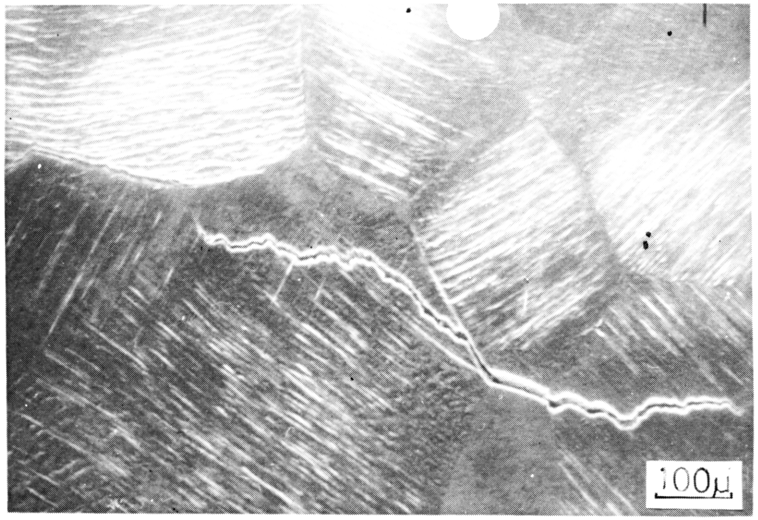


Fig. 8 Intergranular cracks and propagating cracks into grains on 2.5% elongated specimen.

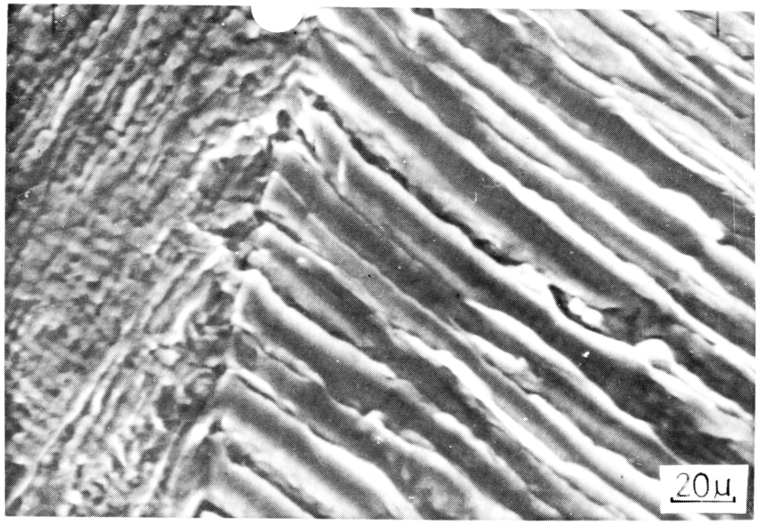


Fig. 9 Slip band cracks along pattern I slips on 6.2% elongated specimen.

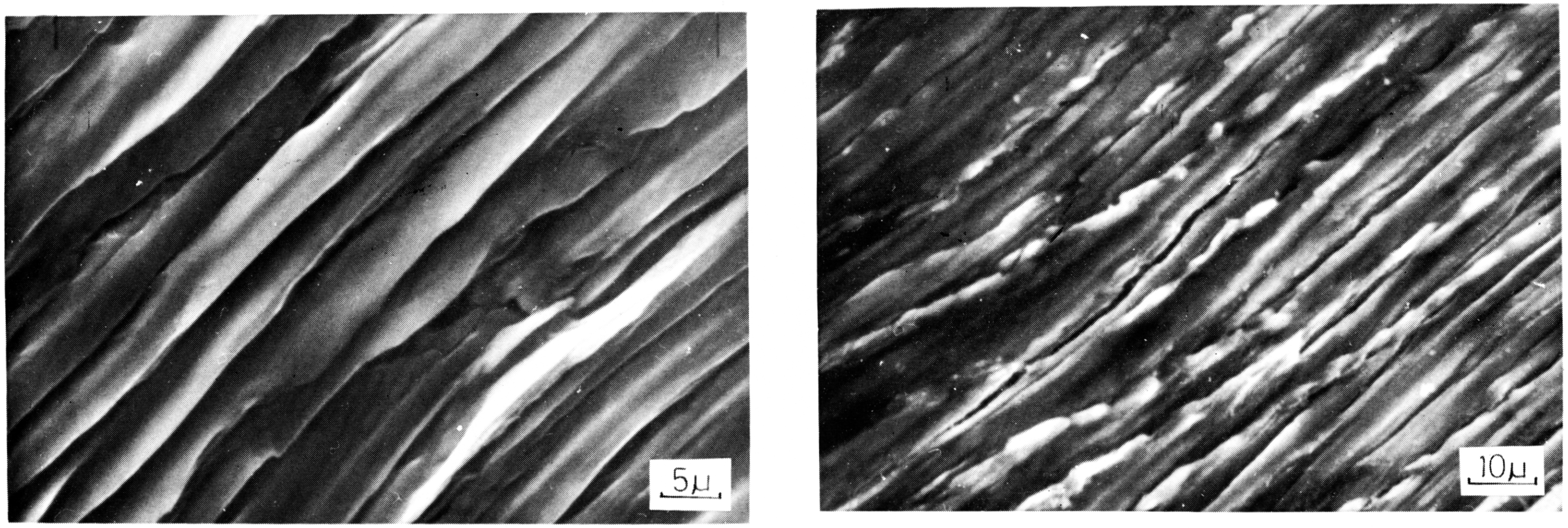
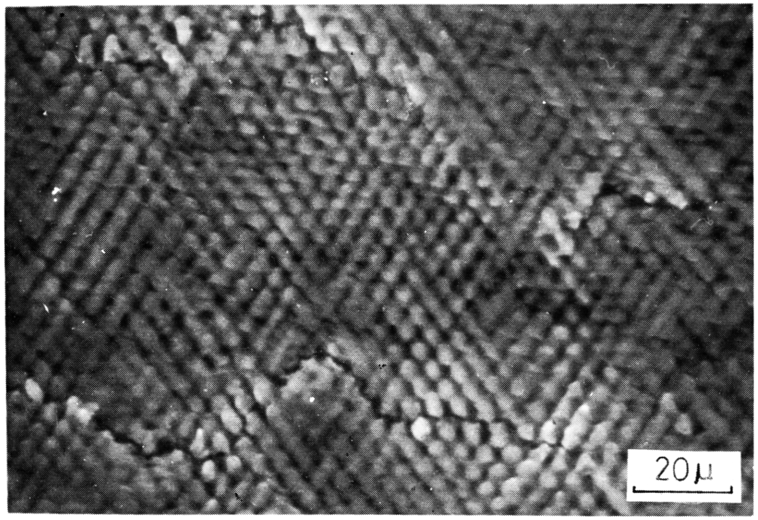


Fig. 10 Slip band cracks along pattern I slips on 7.0% elongated specimen.



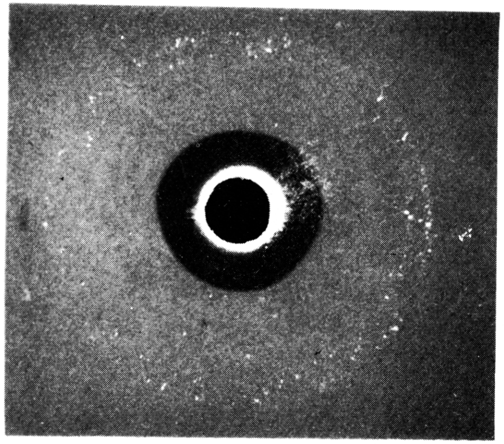
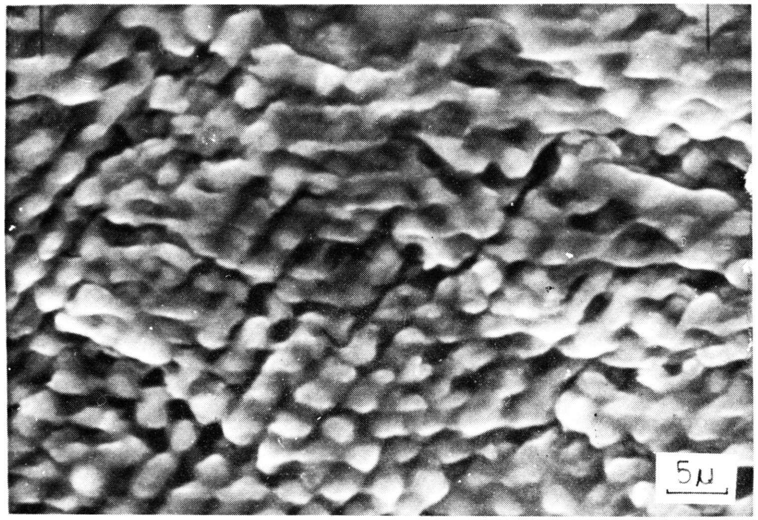


Fig. 12 Micro-beam X-ray diffraction pattern, beam diameter was 0.15 mm, Co K X-ray.



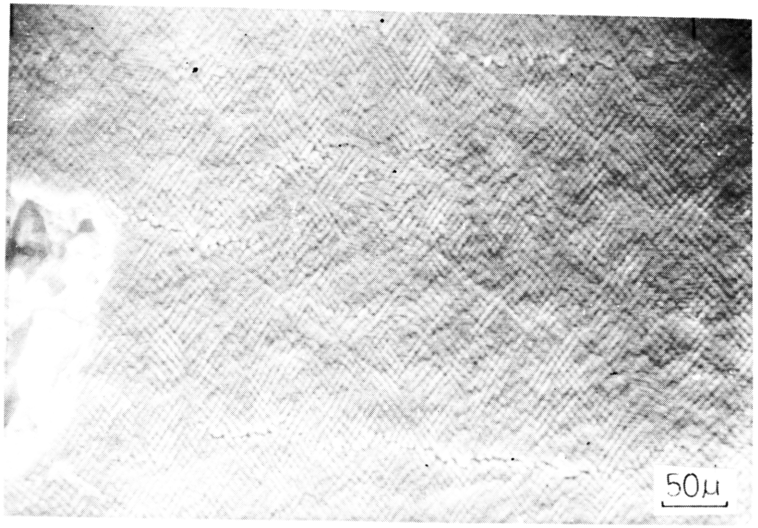


Fig. 11 Sub-boundary cracks on 7.0% elongated specimen.

intergranular cracks decreased and most of cracks occured inside of grains along slop bands of pattern I as shown in Figs. 9 and 10. These figures show the typical slip band cracks, many cracks, however, are difficult to distinguish from slip bands which are seen like intrusions.

The sub-boundary ceacks are shown in Fig. 11, they they could be seen in slip bands of pattern III. These meshlike patterns are seen like mosaics in micrographs of high magnification. Microbeam X-ray diffractions on these regions were Debye ring as shown on Fig. 12, although the sizes of grains were bigger than X-ray beam. This means that the grains have become fine polycrystals. It has been well known that the sizes of subgrains are about 2 μm on transmisson electron micrographs, and agree with the sizes of these mosaics. Then these mosaics can be corresponded to subgrains. Consequently, it can be concluded that the cracks shown in the micrographs have propagated on subgrain boundaries. These cracks can be seen at tips of propagating cracks where are highly deformed, and many microcracks occure at the same time in wide areas.

DISCUSSION

Although the intergranular cracks initiated on annealed specimens, if the specimens had been plastically tensioned, the intergranular cracks decreased, and slip band and sub-boundary cracks increased. This can be considered as follows; The grain boundaries were hardened larger than the others as shown in Fig. 7, because the glides are stopped there and dislocations pile up. As the cyclic strain amplitudes are generally smaller than the strain applied before the cyclic loadings, the slips at the hardened grain boundaries can not increase and never arrive to the boundaries. As the results, the microcrack can not be formed on the grain boundary but formed inside of grain.

The initial intergranular cracks propagated on the grain boundaries up to sufficient length to propagate in perpendicular direction to loadings. The mechanism of crack propagation on intergranular in early stage of fatigue life seems to be the same as the formation of initial crack, because the plastic deformation at the tip of crack is not so large as that at the front of elongated cracks. When the intergranular cracks grew up enough to propagate into grains or the other directions, or stopped at triple points of grain boundaries, the front areas of cracks were greatly deformed. The change from initiations to propagations of cracks have not been able to distinct so clearly, it may be, however, considered that the change from intergranular to transgranular cracks or the stop of propagation for a moment are the change points of propagating mechanism. The slip band cracks have been onserved and discussed by many researchers, then the changes of propagations of them are rested without discussions in this paper.

Slip band cracks on pattern I might be formed likely gliding or tearing crack formation in stage I of fatigue crack propagation on fracture surfaces. However, the initiations of them could not be distinguished from slip bands, thenthey could be distinguished only in the case that the cracks opened or the slip bands had broken as shown in Fig. 10.

Sub-boundary cracks could be observe at comparatively later stage of crack propagation, at the front of elongated cracks, the deformations increased and subgrains developed widely. Many sub-boundary cracks were formed there and one of them connected with the main crack. Then these sub-boundary cracks are one of the crack initiations.

CONCLUSION

Many initial cracks of fatigue on annealed and prestrained pure aluminum were observed by an optical and a scanning electron microscope. The slip bands were also observed and classified to three typed as follows; Pattern I, straight and long slip bands; Pattern II, wavy slip bands and Pattern III, meshlike slip bands. The initial fatigue cracks were formed as follows;

(1) Intergranular cracks occured on annealed specimen and decreased by prestrains.

(2) Slip band cracks occured on plastically prestrained specimens in slip bands of pattern I.

(3) Sub-boundary cracks occured in slip bands of pattern III where were highly deformed

Intergranular cracks must be formed by the mechanism as follows; the slips of pattern I stopped at a grain boundary and dislocations pile up there, then many microcracks occured on the intergranular and connected with each other.

No crack occured in slip bands of pattern II and on the boundaries between grains of patterns II and III.

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